Supervisor Control of Water Distribution Network Actuators under Partial Observation

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Abstract. The present paper proposes an observer for Water Distribution Networks actuators, in order to address the synchronization problem between local and central control stations, caused by communication interruptions. The observer is developed using actuator signals received after communication is restored. The goal of the observer is to resynchronize the actual operating mode of each actuator with the monitored mode of the central control station.

1 Introduction

Water Distribution Networks (WDNs) are large scale systems consisting of many reservoirs, pumping stations, treatment facilities, and pipeline infrastructures (see [1]–[7]). Monitoring and control system architecture of WDNs includes Local Control Stations (LCSs), where all sensors, actuators and local controllers are installed, and a Central Control Station (CCS) coordinating all LCSs ([7]). In the present work, a Discrete Event System (DES) observer for WDNs actuators is proposed. The goal of the observer is to address synchronization between LCSs and CCS, in case of communication loss. The observer is based on a DES model [7] of the transitions of the actuator modes due to commands. Here, the observability of the actuator events will be studied in case of communication loss between LCSs and CCS. The observer identifies, after communication restore, the actual state of the actuator mode, despite the potential occurrence of unobservable events due to communication loss. For details on observability and observers, see [8]-[12].

2 Actuator mode model – Event observability

According to [7], the automaton representing the actuator's modes and transitions is modelled by the 6-tuple (see Figure 1a) $\mathbf{G}_j = (\mathbb{Q}_j, \mathbb{E}_j, f_j, \mathbb{H}_j, x_{j,0}, \mathbb{Q}_j)$, where $j \in \{1,\dots,n_A\}$ and n_A is the number of WDN's actuators. The state set is $\mathbb{Q}_j = \{q_{j,1}, q_{j,2}, q_{j,3}\}$, where $q_{j,1}$, $q_{j,2}$ and $q_{j,3}$ correspond to Off, Auto and Manual mode of the actuator, respectively. The initial state

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is $x_{j,0} = q_{j,1}$. The event set associated with actuator mode changes is $\mathbb{E}_{A,j} = \{e_{j,1},...,e_{j,6}\}$, where $e_{j,1} / e_{j,2} / e_{j,3}$ are the commands of the Auto/Manual/Off mode coming from the dedicated LCS, while $e_{j,4} / e_{j,5} / e_{j,6}$ are the commands of the Auto/Manual/Off mode coming from CCS. The event set associated with changes in the actuator operation is $\tilde{\mathbb{E}}_{A,j} = \{e_{j,7},...,e_{j,12}\}$, where $e_{j,7} / e_{j,8}$ are the commands that initiate/stop operation coming from local switches (manual), $e_{j,9} / e_{j,10}$ are the commands that initiate/stop operation coming from local controllers, and $e_{j,11} / e_{j,12}$ are the commands that initiate/stop operation coming from CCS. The alphabet is $\mathbb{E}_j = \mathbb{E}_{A,j} \cup \tilde{\mathbb{E}}_{A,j}$. The active event sets are $\mathbb{H}_j(q_{j,1}) = \mathbb{E}_{A,j}$, $\mathbb{H}_j(q_{j,2}) = \mathbb{E}_{A,j} \cup \{e_{j,9}, e_{j,10}, e_{j,11}, e_{j,12}\}$ and $\mathbb{H}_j(q_{j,3}) = \mathbb{E}_{A,j} \cup \{e_{j,7}, e_{j,8}\}$. The transitions are $f_j(q_{j,2}, e) = q_{j,2}$, $\forall e \in \tilde{\mathbb{E}}_{A,j} - \{e_{j,7}, e_{j,8}\}$; $f_j(q_{j,3}, e) = q_{j,3}$, $\forall e \in \{e_{j,7}, e_{j,8}\}$; $f_j(q, e_{j,k}) = q_{j,2}$, $\forall k = 1,4$; $f_j(q, e_{j,k}) = q_{j,3}$, $\forall k = 2,5$; and $f_j(q, e_{j,k}) = q_{j,1}$, $\forall k = 3,6$, $\forall q \in \mathbb{Q}_j$.

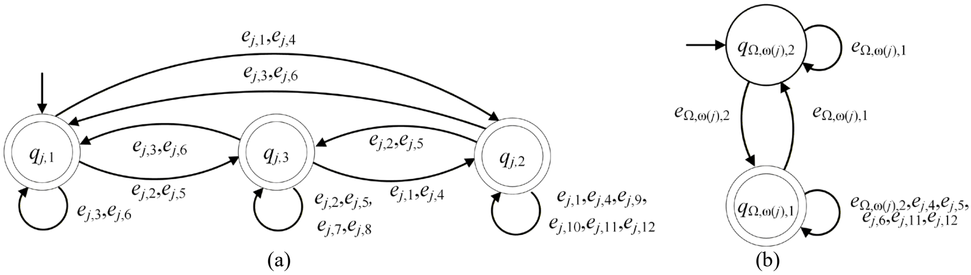

Fig. 1. State diagrams of $\mathbf{G}_j$ and $\mathbf{\Omega}_{\omega(j)}$ [7]

Communication loss between CCS and LCSs may take place for various reasons [7], including equipment malfunctions, meteorological phenomena and human intervention. During communication loss, all events in $\mathbb{E}_{j,C} = \{e_{j,k}, k = 4,5,6,11,12\}$ are not observable by the local controllers. For this case, a DES model $\mathbf{\Omega}_{\omega(j)} = (\mathbb{Q}_{\Omega,\omega(j)}, \mathbb{E}_{\Omega,\omega(j)}, f_{\Omega,\omega(j)}, \mathbb{H}_{\Omega,\omega(j)}, x_{\Omega,\omega(j),0}, \mathbb{Q}_{\Omega,\omega(j),m})$ (see Figure 1b) has been proposed in [7]. $\mathbf{\Omega}_{\omega(j)}$ describes restriction of CCS commands to $\mathbf{G}_j$, during communication loss between CCS and the actuator's LCS indexed by $\omega(j)$. The state set is $\mathbb{Q}_{\Omega,\omega(j)} = \{q_{\Omega,\omega(j),1}, q_{\Omega,\omega(j),2}\}$, where $q_{\Omega,\omega(j),1} / q_{\Omega,\omega(j),2}$ denote that CCS communicates / not communicates with the LCS. The initial state is $x_{\Omega,\omega(j),0} = q_{\Omega,\omega(j),2}$. The marked state set is $\mathbb{Q}_{\Omega,\omega(j),m} = \{q_{\Omega,\omega(j),1}\}$. The alphabet is $\mathbb{E}_{\Omega,\omega(j)} = \{e_{\Omega,\omega(j),1}, e_{\Omega,\omega(j),2}\} \cup \mathbb{E}_{j,C}$, where $e_{\Omega,\omega(j),1} /$ $e_{\Omega,\omega(j),2}$ indicate loss/restore of communication. The active event sets and transitions are $\mathbb{H}_{\Omega,\omega(j)}(q_{\Omega,\omega(j),1}) = \mathbb{E}_{\Omega,\omega(j)}$, $\mathbb{H}_{\Omega,\omega(j)}(q_{\Omega,\omega(j),2}) = \mathbb{E}_{\Omega,\omega(j)} - \mathbb{E}_{j,C}$, $f_{\Omega,\omega(j)}(q, e_{\Omega,\omega(j),1}) = q_{\Omega,\omega(j),2}$, $f_{\Omega,\omega(j)}(q, e_{\Omega,\omega(j),2}) = q_{\Omega,\omega(j),1}$ and $f_{\Omega,\omega(j)}(q_{\Omega,\omega(j),1}, e) = q_{\Omega,\omega(j),1}$, $\forall q \in \mathbb{Q}_{\Omega,\omega(j)}$, $\forall e \in \mathbb{E}_{j,C}$.

During communication loss, all local commands in $\mathbb{E}_{j,l} = \{e_{j,k}, k = 1,2,3,7,...,10\}$ are not observable by CCS. The next section deals with this problem, by proposing an observer that is based on the occasional unobservability of actuator commands from the side of CCS. Namely, during communication loss it holds that the unobservable event set (subset of $\mathbb{E}_j$) is $\mathbb{E}_{j,uo} = \mathbb{E}_{j,l}$. If communication is restored, then $\mathbb{E}_{j,uo} = \varnothing$. In both cases, the observable event set is $\mathbb{E}_{j,o} = \mathbb{E}_j - \mathbb{E}_{j,uo}$. The events $e_{\Omega,\omega(j),1}$ and $e_{\Omega,\omega(j),2}$ are always observable.

Remark 1: The total automaton is the synchronous product ([8], [9]) of $\mathbf{G}_j$ and $\mathbf{\Omega}_{\omega(j)}$.

3 Observer Design

During communication loss, actuator transitions are not observed by CCS. For example, let the actuator be initially in Off mode and, during communication loss, a command triggers transition to Auto mode. Once communication is restored, CCS considers the actuator in Off mode. However, the actuator is already in Auto mode and capable of accepting and executing operation commands. The latter can lead to loss of synchronization of LCSs and CCS, especially when CCS acts as a proxy for signal exchange between LCSs. To determine the actuator mode, an observer, based on operation events, will be developed. The observer is

$$\mathbf{O}_j = (\mathbb{X}_{O,j}, \mathbb{E}_{O,j}, f_{O,j}, \mathbb{H}_{O,j}, \mathbb{X}_{O,j,1}, \mathbb{X}_{O,j,m})\,;\, \mathbb{X}_{O,j} = \{\mathbb{X}_{O,j,1},...,\mathbb{X}_{O,j,5}\}\,,\, \mathbb{X}_{O,j,1} = \{(q_{j,1}, q_{\Omega,\omega(j),2}), (q_{j,2}, q_{\Omega,\omega(j),2}), (q_{j,3}, q_{\Omega,\omega(j),2})\}\,,\ \mathbb{X}_{O,j,2} = \{(q_{j,1}, q_{\Omega,\omega(j),1}), (q_{j,2}, q_{\Omega,\omega(j),1}), (q_{j,3}, q_{\Omega,\omega(j),1})\}\,,$$

$$\mathbb{X}_{O,j,3} = \{(q_{j,1},\ q_{\Omega,\omega(j),1})\}\,,\ \mathbb{X}_{O,j,4} = \{(q_{j,2}, q_{\Omega,\omega(j),1})\}\ ,\ \mathbb{X}_{O,j,5} = \{(q_{j,3}, q_{\Omega,\omega(j),1})\}\,.$$

The marked state set, and the alphabet are $\mathbb{X}_{O,j,m} = \mathbb{X}_{O,j}$ and $\mathbb{E}_{O,j} = \mathbb{E}_j \cup \mathbb{E}_{\Omega,\omega(j)}$. The state diagram of $\mathbf{O}_j$ is in Figure 2. The active event sets and the transitions of $\mathbf{O}_j$ are

$$\mathbb{H}_{O,i,j}(\mathbb{X}_{O,j,1}) = \{e_{\Omega,\omega(j),2}\} \cup \mathbb{E}_{j,C}\,,\ \mathbb{H}_{O,i,j}(\mathbb{X}_{O,j,2}) = \mathbb{E}_j \cup \{e_{\Omega,\omega(j),1}\}\,,$$

$$\mathbb{H}_{O,j}(\mathbb{X}_{O,j,3}) = \mathbb{E}_{A,j} \cup \{e_{\Omega,\omega(j),1}\}\,,\ \mathbb{H}_{O,j}(\mathbb{X}_{O,j,5}) = \mathbb{E}_{A,j} \cup \{e_{j,7}, e_{j,8}\} \cup \{e_{\Omega,\omega(j),1}\}\,,$$

$$\mathbb{H}_{O,j}(\mathbb{X}_{O,j,4}) = \mathbb{E}_{A,j} \cup \{e_{j,9}, e_{j,10}, e_{j,11}, e_{j,12}\} \cup \{e_{\Omega,\omega(j),1}\}\,,\ f_{O,j}(\mathbb{X}_{O,j,1}, e_{\Omega,\omega(j),2}) = \mathbb{X}_{O,j,2}\,,$$

$$f_{O,j}(\mathbb{X}_{O,j,1}, e) = \mathbb{X}_{O,j,1}\,,\ \forall e \in \mathbb{E}_{j,C}\,,\ f_{O,j}(q, e_{\Omega,\omega(j),1}) = \mathbb{X}_{O,j,1}\,,\ f_{O,j}(q, e_{j,1}) = \mathbb{X}_{O,j,4}\,,$$

$$f_{O,j}(q, e_{j,4}) = \mathbb{X}_{O,j,4}\,,\ f_{O,j}(q, e_{j,2}) = \mathbb{X}_{O,j,5}\,,\ f_{O,j}(q, e_{j,5}) = \mathbb{X}_{O,j,5}\,,\ f_{O,j}(q, e_{j,3}) = \mathbb{X}_{O,j,3}\,,$$

$$f_{O,j}(q, e_{j,6}) = \mathbb{X}_{O,j,3}\,, \forall q \in \mathbb{X}_{O,j} - \{\mathbb{X}_{O,j,1}\}\,,\ f_{O,j}(q, e) = \mathbb{X}_{O,j,4}\,, \forall q \in \{\mathbb{X}_{O,j,2}, \mathbb{X}_{O,j,4}\}$$

$$\forall e \in \{e_{j,k}, k = 9,...,12\}\,,\ f_{O,j}(q, e) = \mathbb{X}_{O,j,5}\,, \forall q \in \{\mathbb{X}_{O,j,2}, \mathbb{X}_{O,j,5}\}\ \forall e \in \{e_{j,k}, k = 7,8\}\,.$$

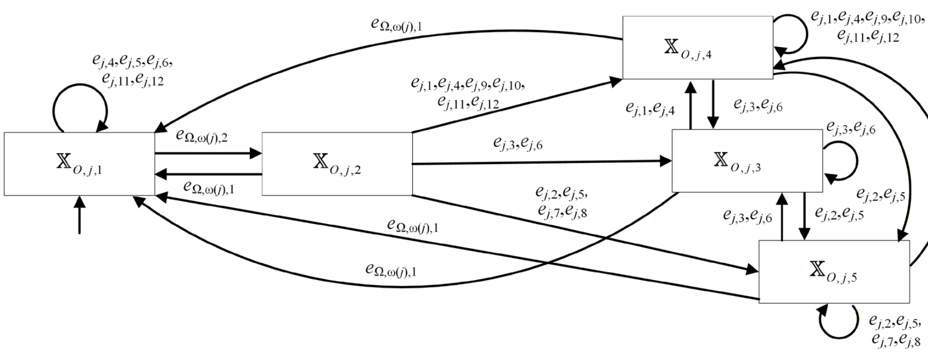

Fig. 2. State diagram of $\mathbf{O}_j$

Remark 2: Actuator operation commands take place more frequently than the change mode commands. In general, actuator change modes occur during maintenance/repair activities, or under exceptional operating conditions in the water station.
Remark 3: An observer must be developed for each actuator installed at the LCSs. Consequently, a bank of observers is constructed to monitor and supervise the total system.
Remark 4: The observers are not combined in synchronous product with the actuator automata or the corresponding supervisors. Thus, the observers do not restrict commands of the WDN.
Remark 5: For the proper observer's operation, when communication is restored, the actuator commands should be sent to the observer provided that they are not restricted by the automaton $\mathbf{G}_j$.

4 Conclusions

An observer for WDNs actuators has been proposed, toward the solution of the synchronization problem between local and central control stations, due to communication loss. The observer has been developed, using actuator signals received by CCS after communication is restored. The goal of the observer is to resynchronize the actual operating mode of each actuator with the corresponding mode monitored by CCS.

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